

RESEARCH

Open Access

Ultrasonic studies of ternary liquid mixtures of N,N-dimethylformamide, nitrobenzene, and cyclohexane at different frequencies at 318 K

Manoj Kumar Prahara^{1*}, Abhiram Satapathy², Prativarani Mishra^{2*} and Sarmistha Mishra²**Abstract**

The ultrasonic velocity, density, and viscosity have been measured for ternary mixtures of nitrobenzene, N,N-dimethylformamide, and cyclohexane at temperature $T = 318$ K at different frequencies such as 2, 4, 6, and 8 MHz. The experimental data have been used to calculate the acoustical and thermodynamical parameters like adiabatic compressibility, free length, free volume, internal pressure, acoustic impedance, Gibbs free energy, and their excess values. In particular, it is seen that the response of these parameters to frequency is less prominent in comparison to that of the ternary mixtures containing N,N-dimethylformamide, cyclohexane, and chlorobenzene.

Keywords: Ternary mixtures, Ultrasonic velocity, Density, Viscosity**PACS:** 34.20.-b, 34.20.Cf, 34.20.Gj**Background**

Ultrasonic investigation of liquid mixture containing polar and nonpolar components is of considerable importance in understanding intermolecular interaction between the component molecules as that finds application in several industrial and technological processes [1]. Ultrasonic velocity and the derived acoustical parameters like adiabatic compressibility, free length, relaxation time, acoustic impedance, etc., with their excess values, provide valuable information about the molecular environments. This has been studied for various binary and ternary mixtures [2-6] with respect to variation in concentration of the liquids and temperatures. In the present paper, variation of various parameters of ternary mixtures containing nitrobenzene, N,N-dimethylformamide (N,N-DMF), and cyclohexane, with frequency have been studied for different concentrations. The change in these parameters in different compositions of the mixtures of N,N-DMF, cyclohexane, and nitrobenzene with frequency is much smaller than those in the mixture containing N,N-DMF, cyclohexane, and chlorobenzene [7].

DMF is a polar molecule having a dipole moment of the same order as that of nitrobenzene. When it is associated with nitrobenzene, the dipolar-dipolar interaction dominates the dipolar-induced dipolar interaction. The relatively small size of N,N-DMF and its linear aliphatic configuration may be the factor contributing to the volume contraction of the mixture.

Nitrobenzene is relatively a complex molecule, and its non-ideality in all probabilities may be due to the polarity arising out of C-N and N-O bonds. As far as the nitro group is concerned, it rotates freely along the C-N axis which is likely to give more flexibility to the interactions arising due to two highly polar N-O bonds.

Cyclohexane belongs to the alicyclic hydrocarbon. It is highly inert towards an electrophile or nucleophile at ordinary temperature. Cyclohexane being nonpolar is not expected to be involved in any strong interaction with the other components of the mixture [8]. However, dispersive types of interactions are possible between them.

Methods

The mixtures of various concentrations in mole fraction were prepared by taking analytical reagent grade and spectroscopic reagent grade chemicals with minimum assay of 99.9% and obtained from E.Merck Ltd (India). In all the mixtures, the mole fraction of the second

* Correspondence: abitphysics@rediffmail.com[†]Deceased¹PG Department of Physics, Ravenshaw University, Cuttack, Odisha 753003, India

Full list of author information is available at the end of the article

Table 1 Values of density, viscosity, and velocity at 2, 4, 6, and 8 MHz (T = 318 K)

Mole fraction			Density (ρ) ($\text{kg}\cdot\text{m}^{-3}$)	Viscosity (η) ($10^{-3} \text{ N}\cdot\text{s}\cdot\text{m}^{-2}$)	Ultrasonic velocity (U) $\text{m}\cdot\text{s}^{-1}$			
X_1	X_2	X_3			2 MHz	4 MHz	6 MHz	8 MHz
0.0000	0.4000	0.6000	856.69	0.6459	1,170.2	1,168.5	1,166.1	1,164.5
0.0999	0.4000	0.4999	853.91	0.6255	1,185.3	1,183.1	1,180.4	1,178.4
0.1998	0.4000	0.4001	848.35	0.6052	1,199.5	1,197.6	1,195.3	1,193.7
0.3001	0.4000	0.3000	844.64	0.5890	1,210.7	1,208.6	1,206.4	1,204.2
0.4000	0.4000	0.1999	834.44	0.5734	1,229	1,226.8	1,224.5	1,222.6
0.4998	0.4000	0.1001	827.95	0.5595	1,242.6	1,240.1	1,237.5	1,236.4
0.5997	0.4000	0.0000	817.70	0.5376	1,261.7	1,258.8	1,256.9	1,254.9

component, cyclohexane ($X_2 = 0.4$), was kept fixed while the mole fractions of the remaining two (X_1 and X_3) were varied from 0.0 to 0.6, so as to have the mixture of different concentration. There is nothing significant in fixing the mole fraction of the second component at 0.4.

The density, viscosity, and ultrasonic velocity were measured as a function of concentration of the ternary liquid mixture at 2, 4, 6, and 8 MHz and at temperature $T = 318\text{K}$.

Velocity measurement

Ultrasonic velocity measurements were made using an ultrasonic interferometer (Model M-84, supplied by M/S Mittal Enterprises, New Delhi), at 318 K with the accuracy of $\pm 0.1\text{m}\cdot\text{s}^{-1}$. The measuring cell of interferometer is a specially designed double-walled vessel with provision for temperature constancy. An electronically operated digital constant temperature bath (Model SSI-03 Spl, supplied by M/S Mittal Enterprises, New Delhi), operating in the temperature range of -10°C to 85°C with an accuracy of $\pm 0.1^\circ\text{C}$ has been used to circulate water through the outer jacket of the double-walled measuring cell containing the experimental liquid.

Density measurement

The densities of the mixture were measured using a 25-ml specific gravity bottle by relative measurement method with an accuracy of $\pm 0.01 \text{ kg}\cdot\text{m}^{-3}$. The specific gravity bottle with the experimental mixture was im-

mersed in the temperature-controlled water bath. The weight of the sample was measured using an electronic digital balance with an accuracy of $\pm 0.1 \text{ mg}$ (Model: SHIMADZU AX-200, Kyoto, Japan).

Viscosity measurement

An Oswald viscometer (10 ml) with an accuracy of $\pm 0.001 \text{ N}\cdot\text{s}\cdot\text{m}^{-2}$ was used for the viscosity measurement. The flow time was determined using a digital racer stopwatch with an accuracy of $\pm 0.1\text{s}$.

Theoretical aspect

The following thermodynamic parameters were calculated:

- 1 Adiabatic compressibility (β) has been calculated from the ultrasonic velocity (U), and the density (ρ) of the medium using the Newton-Laplace equation [9] as follows:

$$\beta = 1/U^2\rho \quad (1)$$

- 2 Intermolecular free length (L_f) has been determined as follows [10]:

$$L_f = K_T\beta^{1/2}, \quad (2)$$

where K_T is the temperature-dependent constant known as Jacobson's constant ($K_T = 2.131 \times 10^{-6}$ at 318K), and β is the adiabatic compressibility.

Table 2 Values of adiabatic compressibility, free length, and free volume at 2, 4, 6, and 8 MHz

Mole fraction		Adiabatic compressibility (β) ($10^{-10} \text{ m}^2\cdot\text{N}^{-1}$)				Free length (L_f) (10^{-10} m)				Free volume (V_f) ($10^{-7} \text{ m}^3\cdot\text{mol}^{-1}$)			
X_1	X_3	2 MHz	4 MHz	6 MHz	8 MHz	2 MHz	4 MHz	6 MHz	8 MHz	2 MHz	4 MHz	6 MHz	8 MHz
0.0000	0.6000	8.5242	8.5491	8.5843	8.6079	0.593	0.5938	0.5951	0.5959	3.0687	3.0620	3.0526	3.0463
0.0999	0.4999	8.3355	8.3665	8.4049	8.4334	0.5864	0.5875	0.5888	0.5898	3.0557	3.0472	3.0367	3.0290
0.1998	0.4001	8.1927	8.2187	8.2504	8.2725	0.5813	0.5823	0.5834	0.5842	3.0333	3.0261	3.0174	3.0113
0.3001	0.3000	8.0771	8.1052	8.1348	8.1646	0.5772	0.5782	0.5793	0.5803	2.9606	2.9529	2.9448	2.9367
0.4000	0.1999	7.9342	7.9627	7.9926	8.0175	0.5721	0.5731	0.5742	0.5751	2.8994	2.8916	2.8835	2.8768
0.4998	0.1001	7.8223	7.8539	7.8869	7.9009	0.568	0.5692	0.5704	0.5709	2.8009	2.7924	2.7837	2.7799
0.5997	0.0000	7.6824	7.7178	7.7412	7.7659	0.5629	0.5642	0.5651	0.566	2.7691	2.7596	2.7533	2.7468

Table 3 Values of internal pressure, viscous relaxation time, and Gibb's free energy 2, 4, 6, and 8 MHz

Mole fraction		Internal pressure (Π_i) ($\times 10^6 \text{ N}\cdot\text{m}^{-2}$)				Viscous relaxation time (τ) ($\times 10^{-12} \text{ s}$)				Gibbs free energy (ΔG) ($\times 10^{-20} \text{ kJ}\cdot\text{mol}^{-1}$)			
X_1	X_3	2 MHz	4 MHz	6 MHz	8 MHz	2 MHz	4 MHz	6 MHz	8 MHz	2 MHz	4 MHz	6 MHz	8 MHz
0.0000	0.6000	312.79	313.01	313.33	313.55	0.7341	0.7362	0.7392	0.7413	0.6945	0.6958	0.6976	0.6988
0.0999	0.4999	322.67	322.97	323.34	323.61	0.6951	0.6977	0.7009	0.7033	0.6706	0.6722	0.6742	0.6757
0.1998	0.4001	332.93	333.19	333.51	333.74	0.6610	0.6631	0.6657	0.6675	0.6485	0.6499	0.6516	0.6528
0.3001	0.3000	346.58	346.88	347.19	347.51	0.6343	0.6365	0.6389	0.6412	0.6304	0.6319	0.6335	0.6351
0.4000	0.1999	359.29	359.61	359.95	360.23	0.6066	0.6088	0.6111	0.6130	0.6108	0.6123	0.614	0.6154
0.4998	0.1001	375.99	376.37	376.77	376.93	0.5835	0.5859	0.5883	0.5894	0.5937	0.5955	0.5973	0.5981
0.5997	0.0000	390.29	390.73	391.03	391.34	0.5507	0.5532	0.5549	0.5566	0.5683	0.5703	0.5716	0.5730

- 3 Free volume (V_f) in terms of ultrasonic velocity (U) and the viscosity (η) of liquid is [11] as follows:

$$V_f = (M_{\text{eff}} U / k \eta)^{3/2}, \quad (3)$$

where M_{eff} is the effective molecular weight of the mixture ($M_{\text{eff}} = \sum m_i X_i$, where m_i and X_i are the molecular weight and mole fraction of individual constituents, respectively), k is a temperature-independent constant which is equal to 4.281×10^9 [12] for all liquids.

- 4 Internal pressure (Π_i) can be calculated using the relation [13] as follows:

$$\Pi_i = bRT(k\eta/U)^{1/2}(\rho^{2/3}/M_{\text{eff}}^{7/6}), \quad (4)$$

where b stands for cubic packing, which is assumed to be 2 for all liquids, k is a dimensionless constant independent of temperature and nature of liquids. Its value is 4.281×10^9 . T is the absolute temperature in Kelvin, M_{eff} is the effective molecular weight, R is the universal gas constant, η is the viscosity of solution in $\text{Ns}\cdot\text{m}^{-2}$, U is the ultrasonic velocity in $\text{m}\cdot\text{s}^{-1}$, and ρ is the density in $\text{kg}\cdot\text{m}^{-3}$ of solution.

- 5 Relaxation time (τ) in terms of adiabatic compressibility (β) and viscosity (η) of the liquid is as follows:

$$\tau = 4/3.(\beta.\eta), \quad (5)$$

where β is the adiabatic compressibility, and η is the viscosity of the mixture.

- 6 The Gibbs free energy (ΔG) can be calculated using the relation as follows:

$$\Delta G = k_B.T.\ln(k_B.T.\tau/h), \quad (6)$$

where τ is the viscous relaxation time, T is the absolute temperature, k_B is Boltzmann's constant, and h is Planck's constant.

- 7 Acoustic impedance (Z) is given as follows:

$$Z = U.\rho, \quad (7)$$

where U and ρ are the velocity and density of the mixture, respectively.

- 8 Absorption coefficient or attenuation coefficient is a characteristic of the medium, and it depends on the external condition like temperature, pressure, and frequency of measurement. It is given by the following [14]:

$$\alpha = 8\pi^2\eta f^2/3\rho U^2, \quad (8)$$

where f is the frequency of ultrasonic wave.

Excess parameters

In order to study the non-ideality of the liquid mixtures, the difference between the values of the acoustic and

Table 4 Values of acoustic impedance at 2, 4, 6, and 8 MHz

Mole fraction		Acoustic impedance (Z) ($\times 10^6 \text{ kg}\cdot\text{m}^2\cdot\text{s}^{-1}$)				Absorption coefficient (α) ($\text{np}\cdot\text{m}^{-1}$)			
X_1	X_3	2 MHz	4 MHz	6 MHz	8 MHz	2 MHz	4 MHz	6 MHz	8 MHz
0.0000	0.6000	1.0025	1.001	0.999	0.9976	49.54	199.04	450.61	804.40
0.0999	0.4999	1.0121	1.0103	1.008	1.0062	46.32	186.31	422.07	754.17
0.1998	0.4001	1.0176	1.016	1.014	1.0127	43.52	174.93	395.87	706.60
0.3001	0.3000	1.0226	1.0208	1.019	1.0171	41.38	166.38	376.42	672.86
0.4000	0.1999	1.0255	1.0237	1.0218	1.0202	38.98	156.77	354.72	633.56
0.4998	0.1001	1.0288	1.0267	1.0246	1.0237	37.09	149.25	337.93	602.36
0.5997	0.0000	1.0317	1.0293	1.0278	1.0261	34.47	138.84	313.80	560.54

Table 5 Excess values of adiabatic compressibility, free length, and free volume at 2, 4, 6, and 8 MHz

Mole fraction		Adiabatic compressibility (β^E) ($10^{-10} \text{ m}^2 \cdot \text{N}^{-1}$)				Free length (L_f^E) (10^{-10} m)				Free volume (V_f^E) ($10^{-7} \text{ m}^3 \cdot \text{mol}^{-1}$)			
X_1	X_3	2 MHz	4 MHz	6 MHz	8 MHz	2 MHz	4 MHz	6 MHz	8 MHz	2 MHz	4 MHz	6 MHz	8 MHz
0.0000	0.6000	1.965	1.975	1.999	2.009	0.0828	0.0831	0.0839	0.0842	0.3911	0.3885	0.3820	0.3793
0.0999	0.4999	1.672	1.687	1.714	1.727	0.0715	0.0719	0.0729	0.0733	0.3867	0.3828	0.3755	0.3718
0.1998	0.4001	1.424	1.433	1.452	1.458	0.0616	0.0618	0.0625	0.0627	0.3723	0.3702	0.3648	0.3631
0.3001	0.3000	1.203	1.212	1.228	1.240	0.0526	0.0529	0.0534	0.0538	0.3074	0.3053	0.3007	0.2973
0.4000	0.1999	0.956	0.964	0.980	0.986	0.0428	0.0430	0.0436	0.0438	0.2549	0.2532	0.2487	0.2471
0.4998	0.1001	0.740	0.749	0.767	0.761	0.0340	0.0342	0.0349	0.0346	0.1646	0.1628	0.1578	0.1596
0.5997	0.0000	0.496	0.507	0.515	0.519	0.0242	0.0245	0.0248	0.0249	0.1416	0.1391	0.1369	0.1361

thermodynamic parameters of the real mixture (A_{exp}) and those corresponding to an ideal mixture (A_{id}) were computed using the equation as follows:

$$A^E = A_{\text{exp}} - A_{\text{id}}$$

where, A^E represents the excess parameter, $A_{\text{id}} = \sum A_i X_i$, $i = 1$ to n , A_i is any parameter, and X_i is the mole fraction of the liquid components.

Results and discussion

The experimental data relating to density, viscosity, and velocity at 318 K for frequencies 2, 4, 6, and 8 MHz for the given mixture have been presented in Table 1. Calculated values of adiabatic compressibility, free length, free volume, internal pressure, viscous relaxation time, Gibbs free energy, acoustic impedance, and absorption coefficient are presented in Tables 2, 3, 4, and their excess values are presented in Tables 5, 6, 7.

The intermolecular free lengths as well as the relaxation time are properties of liquid mixtures which mainly affect the ultrasonic velocity. The velocity decreases with the increase of frequency. This is confirmed by the fact that both free length and relaxation time increase with the increase of frequency. Since the association of the interacting molecules varies with the frequency of the ultrasonic wave, cohesive force also

varies. Cohesive force as well as internal pressure increases with the increase of frequency.

The increase in adiabatic compressibility (Figure 1), suggests minimum interaction between unlike molecules. Adiabatic compressibility is given by the relation, $\beta = 1/U^2 \cdot \rho$, which shows that as frequency increases, velocity decreases at a particular density and hence adiabatic compressibility increases. This also confirms the fact that free length increases (Figure 2), with the increase in frequency.

Acoustic impedance decreases with the increase in frequency. This supports the possibility of weak interaction between unlike molecules. Acoustic impedance is also given by the product of the ultrasonic velocity and density $Z = U\rho$ and is used for assessing the absorption of sound in a medium. As frequency increases, absorption coefficient increases rapidly as it is proportional to the square of the frequency.

The Gibbs free energy (ΔG) increases with the increase in frequency. An increasing value of ΔG suggests that the closer approach of unlike molecules is due to hydrogen bonding. The increase in ΔG suggests shorter time for the rearrangement of molecules in the mixture. When frequency increases, the energy imparted to the molecules obviously expedites the rearrangement procedure.

The excess parameters are a measure of deviation from ideal behavior and are found to be highly sensitive to intermolecular interactions between component

Table 6 Excess values of internal pressure, acoustic impedance, and Gibbs free energy (ΔG^E) at 2, 4, 6, and 8 MHz

Mole fraction		Internal pressure (Π^E) ($\times 10^6 \text{ N} \cdot \text{m}^{-2}$)				Acoustic impedance (Z^E) ($\times 10^6 \text{ kgm}^2 \cdot \text{s}^{-1}$)				Gibbs free energy (ΔG^E) ($\times 10^{-20} \text{ kJ} \cdot \text{mol}^{-1}$)			
X_1	X_3	2 MHz	4 MHz	6 MHz	8 MHz	2 MHz	4 MHz	6 MHz	8 MHz	2 MHz	4 MHz	6 MHz	8 MHz
0.0000	0.6000	-52.69	-52.64	-52.44	-52.38	-0.3297	-0.3299	-0.3312	-0.3316	0.0723	0.0727	0.0738	0.0743
0.0999	0.4999	-51.11	-51.03	-50.79	-50.70	-0.2868	-0.2873	-0.2888	-0.2894	0.0604	0.0610	0.0624	0.0630
0.1998	0.4001	-49.27	-49.26	-49.09	-49.07	-0.2487	-0.2487	-0.2498	-0.2499	0.0502	0.0505	0.0515	0.0517
0.3001	0.3000	-44.12	-44.11	-43.95	-43.87	-0.2109	-0.211	-0.2119	-0.2124	0.0440	0.0443	0.0452	0.0457
0.4000	0.1999	-39.71	-39.72	-39.55	-39.54	-0.1748	-0.1748	-0.1757	-0.1758	0.0365	0.0367	0.0376	0.0378
0.4998	0.1001	-31.39	-31.37	-31.16	-31.28	-0.1387	-0.1387	-0.1398	-0.1391	0.0314	0.0317	0.0327	0.0323
0.5997	0.0000	-25.40	-25.35	-25.26	-25.26	-0.1026	-0.1027	-0.1032	-0.1031	0.0181	0.0185	0.0189	0.0190

Table 7 Excess values of viscous relaxation time (τ^E) at 2, 4, 6, and 8 MHz

Mole fraction		Viscous relaxation time (τ^E) ($\times 10^{-12}$ s)			
X_1	X_3	2 MHz	4 MHz	6 MHz	8 MHz
0.0000	0.6000	0.1105	0.1114	0.1135	0.1145
0.0999	0.4999	0.0859	0.0872	0.0894	0.0906
0.1998	0.4001	0.0660	0.0667	0.0682	0.0688
0.3001	0.3000	0.0535	0.0541	0.0554	0.0564
0.4000	0.1999	0.0401	0.0406	0.0419	0.0423
0.4998	0.1001	0.0313	0.0318	0.0332	0.0327
0.5997	0.0000	0.0128	0.0134	0.0140	0.0142

molecules of the mixture. Weak interaction between unlike molecules gives positive excess values whereas those of dipole-dipole, dipole-induced dipole, charge transfer, and hydrogen bonding between unlike molecules gives negative excess parameters.

The excess values of relaxation time, internal pressure, acoustic impedance, and Gibbs free energy indicate that the interaction between the molecules does not seem to vary very much in strength with changing frequency in the case of N,N-dimethylformamide + cyclohexane + nitrobenzene mixture while the change is conspicuous in N,N-dimethylformamide + cyclohexane + chlorobenzene mixture [7]. This may be due to the fact that nitrobenzene has a large dipole moment in comparison to chlorobenzene. Hence, intermolecular interaction in the case of the mixture containing nitrobenzene is large compared to that containing chlorobenzene.

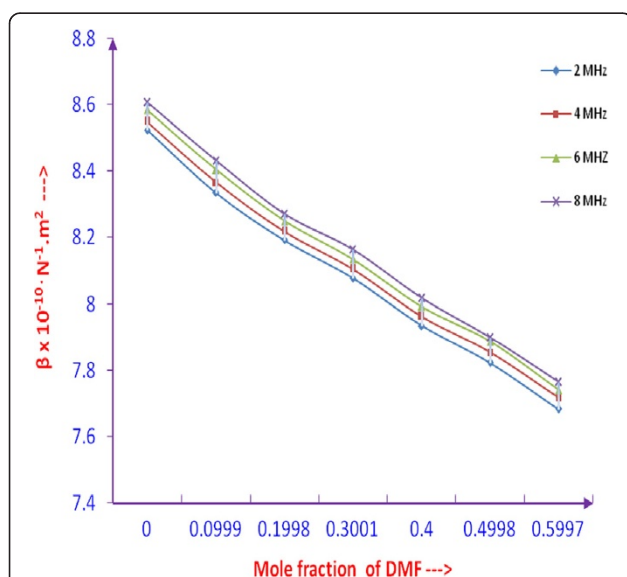


Figure 1 Variation of adiabatic compressibility with mole fraction of DMF.

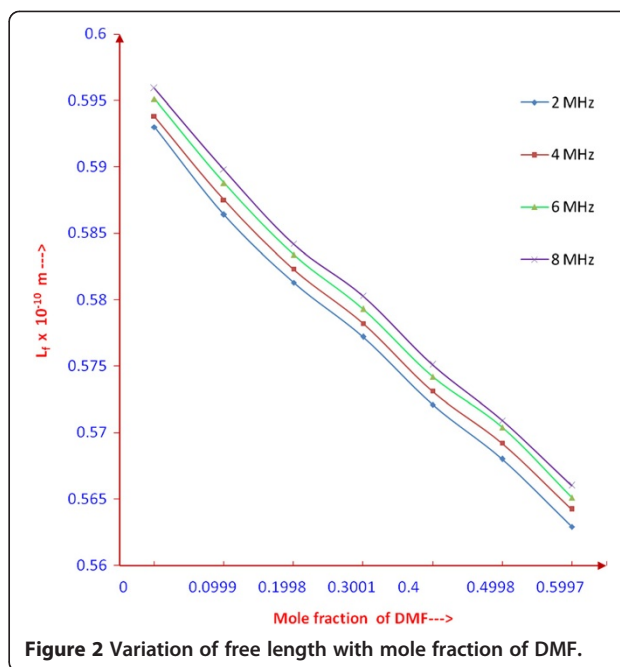


Figure 2 Variation of free length with mole fraction of DMF.

Conclusion

N,N-dimethylformamide and nitrobenzene mixture are characterized by the interaction between the π electron cloud of the benzene ring with the delocalized π electron cloud over the nitrogen and oxygen atoms of the nitro group resulting in the formation of a weak interaction between them. However, the mixture with chlorobenzene is more reactive [7]. The chlorine atom in chlorobenzene is bonded with sp^3 hybridized carbon atom and can be removed easily. This shows that rate of reaction with chlorobenzene is faster than with nitrobenzene.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

MKP has performed the experimental and calculation work. MKP, AS, and SM analyzed the data and the results. SM wrote the manuscript. PR provided guidance at various stages. All authors studied, reviewed, and finally approved the manuscript.

Authors' information

MKP is working as Sr. Lecturer in the Department of Physics of Ajay-Binay Institute of Technology, Cuttack, Odisha since 2009 and has 15 years of experience in teaching Physics, Physics of Semiconductor Devices and Material Sciences to B.Tech. students. He is also a Ph.D. Scholar of Ravenshaw University and got three years of research experience. He has published nine research articles in his area of research in different national and international journals. AS is working as Associate Professor in the Department of Physics of Ajay-Binay Institute of Technology, Cuttack, Odisha since 1998 and has 15 years of experience in teaching Physics, Physics of Semiconductor Devices and Materials Sciences to B.Tech. students. He had his Ph.D. from Fakir Mohan University, Balasore in 2011 and got seven years of research experience. He has published 14 research articles in his area of research in different national and international journals. PM is a retired Professor of the Department of Physics, Ravenshaw University in the year 2002 and had worked as Director (Academic) of Ajay-Binay Institute of Technology, Cuttack, Odisha. She expired on 12 Nov. 2012. She had her Ph. D. from Utkal University, Odisha. She had 36 years of teaching and research experience in

Physics. She had many publications in journals of national and international repute. SM is a retired Professor and Head of the Department of Physics, Ravenshaw University in the year 2006 and is presently working as a visiting Professor in the Department of Physics of Ajay-Binay Institute of Technology, Cuttack, Odisha. She had her Ph. D. from Utkal University, Odisha. She has 36 years of teaching and research experience in Physics. She has many publications in journals of national and international repute.

Acknowledgements

We are thankful to the Management of Ajay Binay Institute of Technology, CDA, Cuttack, for providing the infrastructure as an initiation for the improvement of research activities in the Institute. We are also thankful to the Department of Physics, Ravenshaw University for providing guidance through their experienced faculty members.

Author details

¹PG Department of Physics, Ravenshaw University, Cuttack, Odisha 753003, India. ²Department of Physics, ABIT, CDA, Sector-1, Cuttack, Odisha 753014, India.

Received: 9 October 2012 Accepted: 28 April 2013

Published: 11 May 2013

References

1. Thirumaran, S, Jayakumar, J: Ultrasonic study of n-alkanols in toluene with nitrobenzene. *Ind. J. Pure & Appl. Phys.* **47**, 265–272 (2009)
2. Praharaj, MK, Satapathy, A, Mishra, S, Mishra, PR: Ultrasonic studies of molecular interactions in pyridine + N-N dimethylformamide + cyclohexane ternary liquid mixtures at different temperatures. *Int. J. of Chem. and Phar. Sc.* **3**(3), 6–14 (2012)
3. Oswet, SL, Patel, AT: Speeds of sound, isentropic compressibilities, and excess volumes of binary mixtures 2. Mono-n-alkylamines with cyclohexane and benzene. *J. Chem. Eng. Data* **40**, 194–198 (1995)
4. Ali, A, Nain, Abida, AK: Ultrasonic and volumetric studies of molecular interactions in acetonitrile + 1-alkanol (C₆, C₈, C₁₀) binary liquid mixtures at different temperatures. *J. of the Chinese Chem. Soc.* **51**, 477–485 (2004)
5. Praharaj, MK, Satapathy, A, Mishra, S, Mishra, PR: Ultrasonic study of ternary liquid mixture containing substituted benzene. *Arch. of Phys. Res.* **3**(3), 192–200 (2012)
6. Paikaray, R, Mishra, S: Study of molecular interaction and association in binary mixture of dehp (Di-(2-ethyl-hexyl) phosphoric acid) with N-butyl chloride at different temperatures. *J. of Acou. Soc. of Ind.* **37**(1), 20–24 (2010)
7. Praharaj, MK, Satapathy, A, Mishra, S, Mishra, PR: Study of thermodynamic and transport properties of ternary liquid mixture at different frequencies. *J. of Chem. & Phar. Res.* **4**(4), 1910–1920 (2012)
8. Thirumaran, S, Jayalakshmi, K: Molecular interaction studies on n-alkanols in cyclohexane with DMF at 303 K. *Arch. of Appl. sc. Res.* **1**(2), 24–31 (2009)
9. Rao, DN, Krishnaiah, A, Naidu, PR: Excess thermodynamic properties of liquid ethylenediamine + an aromatic hydrocarbon. *Acta.Chim. Acad. Sci. Hung* **107**(1), 49–55 (1981)
10. Nikam, PS, Hasan, M: Ultrasonic velocity and apparent molar compressibility of Trichloro acid in aqueous ethanol. *Asian J. of Chem.* **5**(2), 319–321 (1993)
11. Prasad, N: Excess free volume and internal pressure of binary solutions of N, N –dimethyl aniline and halomethanes. *J. Pure. App. Ultrason.* **25**, 25–30 (2003)
12. Palani, R, Balakrishnan, S: Acoustical properties of ternary mixtures of 1-alkanols in di-isopropyl ether and 2,2,2-trifluoroethanol mixed solvent. *Ind. J. of pure & Appl. Phy.* **48**, 544–650 (2010)
13. Varada, R, Sreenivasulu, A, Raghuraman, G: Ultrasonic attenuation in aqueous dispersion of polytetrafluoroethylene. *Ind. J. of Chem. Tech.* **1**, 302–304 (1994)
14. Das, JK, Dash, SK, Swain, N, Swain, BB: Ultrasonic Investigation in a polar- polar system, methyl-Isobutyl Ketone and Aliphatic alcohols. *J. Molecular Liquids.* **81**, 163–179 (1999)

doi:10.1186/2251-7235-7-23

Cite this article as: Praharaj et al.: Ultrasonic studies of ternary liquid mixtures of N-N-dimethylformamide, nitrobenzene, and cyclohexane at different frequencies at 318 K. *Journal of Theoretical and Applied Physics* 2013 **7**:23.

Submit your manuscript to a SpringerOpen[®] journal and benefit from:

- Convenient online submission
- Rigorous peer review
- Immediate publication on acceptance
- Open access: articles freely available online
- High visibility within the field
- Retaining the copyright to your article

Submit your next manuscript at ► springeropen.com